Automation and Autonomy for Robotic Spacecraft

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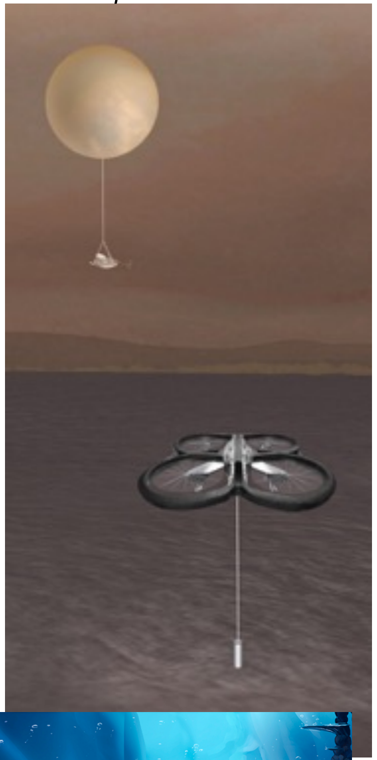
Vision for the Future of Autonomy at JPL

- Space exploration involves spacecraft operating in harsh and unforgiving environments

- JPL is pioneering resilient, self-aware, and autonomous systems able to weigh risk and make decisions locally to ensure that tomorrow's missions are a success
  - The topic of Autonomous Systems and Artificial Intelligence is identified as a key strategic future capability in the JPL Strategic Implementation Plan

- Key characteristics of future missions:
  - Goal-directed operation, allowing operators to focus on objectives and oversight
  - Self-sufficient planning, scheduling, and control, including internal management of resources and redundancy, coordination of both engineering tasks and science observations, and recovery from anomalies
  - Real-time assessment of situations given set of objectives and utilizing models of system and environment
  - Capabilities for learning and model adaptation based on observations of system and environment

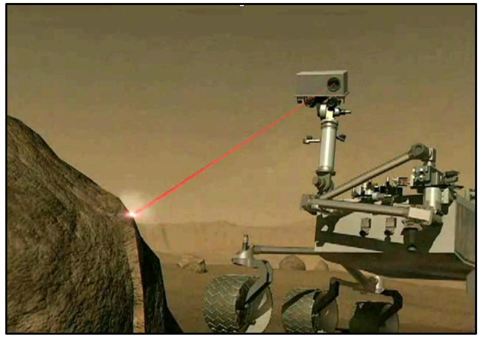
Global exploration of Titan

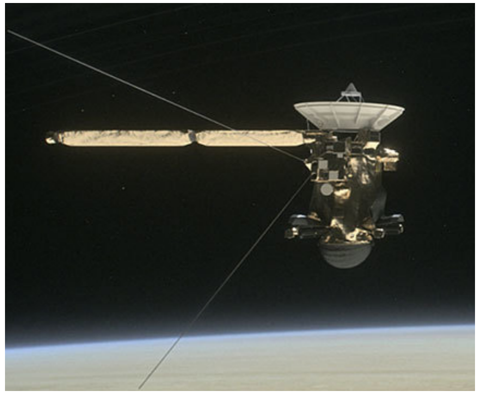


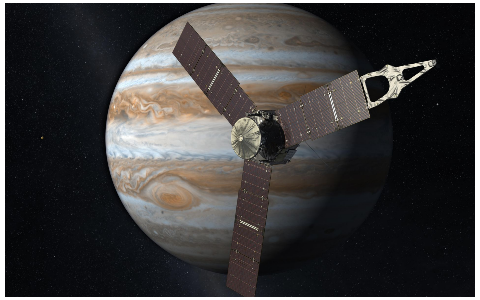
Submersible in the ocean of Europa

Autonomy and Automation

- Autonomy is the ability of a system to achieve goals while operating independently of external control (*2015 NASA Technology Roadmap*)
  - Requires self-directedness (to achieve goals)
  - Requires self-sufficiency (to operate independently)
- Automation is the replacement of routine manual processes with software/hardware processes that follow a step-by-step sequence (*Autonomous and Autonomic Systems, Truszkowski, et al*)
- JPL currently deploys autonomous systems that:
  - Protect systems from detected faults and hazardous conditions (fault protection)
  - Perform critical events despite the presence of failures (orbit insertion; entry, descent and landing)
  - Increase mission effectiveness and return (auto-navigation, feature detection and science observation re-targeting)


Curiosity Rover


Cassini


Juno

Present Challenges

- Systems must work the first time, in configurations and environments that cannot be fully represented before launch
    - Nature of missions (exploration) also typically means limited data available

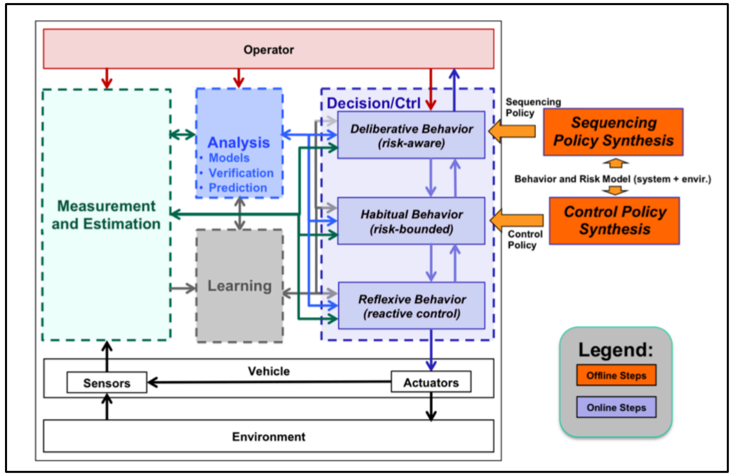
- Implementations are time-consuming to develop and difficult to validate
    - Particularly for protection of safety-critical engineering functions
    - This scales poorly as system and environmental complexity grow

- Persistent questions on completeness of design, and adequacy of V&V
    - Addressed by multiple levels of review and cross-cutting analyses

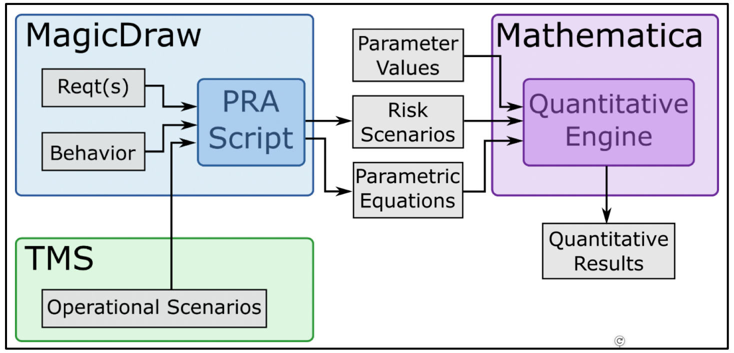
- Autonomous fault recovery limited to specific scenarios and fault cases
    - Due to size of state space and *a priori* elaboration of on-board responses

Autonomy Focus Areas

- Architecture
  - Mission-wide evolvable architecture that enables the integration and deployment of state-of-the-art control and machine reasoning technologies
- Methodology
  - Processes and tools for assembly, coordination, and analysis of information in a systematic fashion that ensures completeness and accuracy, that results in a reliable, affordable, operable system
- Computing
  - High-performance, fault-tolerant, multi-processor computing platform
- Assessments and guarantees of system behavior
  - Enabled by principled design techniques and advancements in simulation and formal methods
- Iterative development
  - Iterative development of operational capabilities in a rapid prototyping facility, progressively increasing the scope of the deployed autonomy platform
- Partnerships and collaborations
  - Leverage external investments in autonomy, artificial intelligence and other related technologies



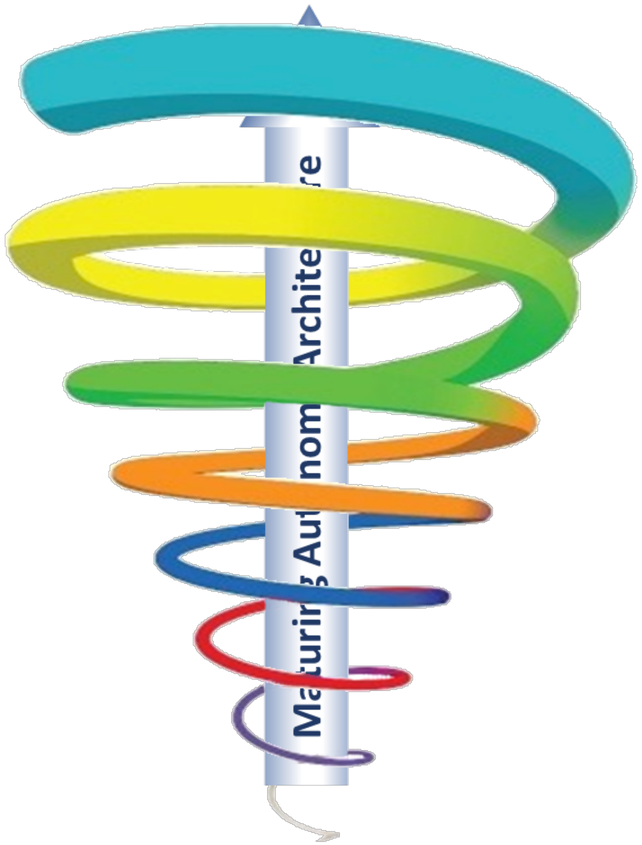
Resilient Spacecraft Executive Architecture



Model-based Probabilistic Risk Assessment

Approach: Staged Evolution of Capability

- Stage 1: “Resilient System”
  - System performs resource management and health management functions. Executes “tactical” activity plans provided by operations team. Uses and adapts models of internal state. Control via closed-loop commanding. Adapts detailed plan to address minor anomalies.
- Stage 2: “Independent System”
  - System generates tactical activity plan based on science directives (“strategic plan”) provided by science team. Uses and adapts models of internal state and environment. Reduced mission operations team needed.
- Stage 3: “Self-Directed System”
  - System develops science strategic plan and tactical plans based on high-level objectives. Responds to novelty by adjusting plans within context of objectives. Reduced science operations team needed.

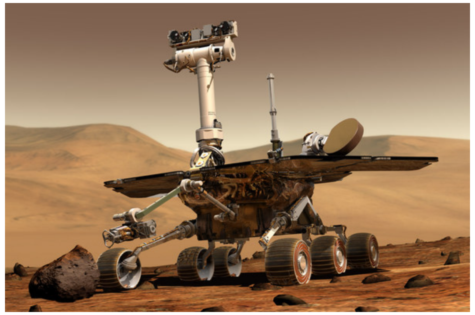


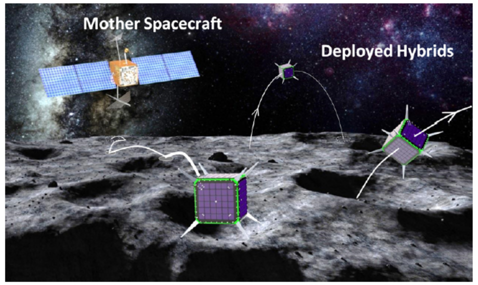
Summary

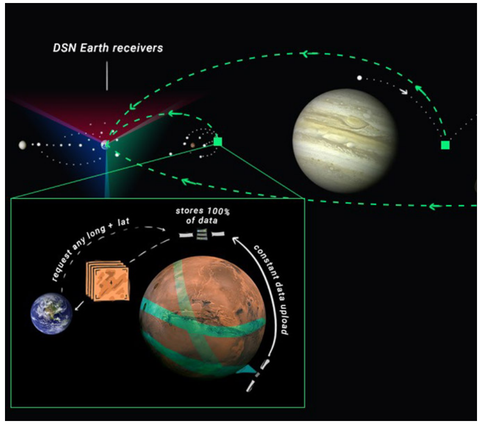
- A close partnership between people and semi-autonomous machines has enabled decades of space exploration, but to significantly expand our reach, our systems must become more capable
  - This need is documented in the comprehensive JPL Strategic Implementation Plan, available to the public here

- We intend to develop and demonstrate self-directed and independent systems capable of performing science missions with high confidence, despite failure or unanticipated circumstances, to
  - improve robustness,
  - increase science return, and
  - greatly expand opportunities for exploration

- Our approach is iterative and evolutionary, establishing the necessary engineering foundations to design autonomous systems with guarantees of behavior
  - Needed capabilities also depend on technology development in areas such as artificial intelligence, machine learning, model-based systems engineering, software development and robotics







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